INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: SINGLE-SIDEBAND COMMUNICATION SYSTEM
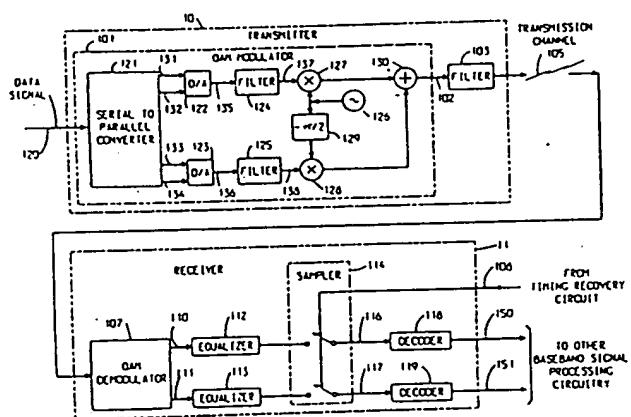
(57) Abstract

A bandwidth reduction technique for use in digital systems wherein elements of a data signal modulate quadrature-related carriers. This modulation, referred to as quadrature amplitude modulation (QAM) or phase shift keying (PSK), generates a double-sideband signal which is transmitted in a variety of communications systems. In accordance with the present invention, the above-described double-sideband signal is filtered (103) to form a single-sideband signal prior to transmission. While this use of a single-sideband signal, in lieu of a double-sideband signal, effectively doubles the system capacity by permitting the use of two communications systems in the bandwidth previously occupied by one system, the filtering process (103) contaminates the data signal elements. To recover the data signal elements at the receiver, received signal elements are formed by extracting the carrier signals (107). Next, these received signal elements are altered by prese-lected quantities to form estimates of each data signal element (301, 302...307). A comparison of the formed estimates (318) against the set of permissible values for each data signal element then determines which estimate is correct.

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SINGLE-SIDEBAND COMMUNICATION SYSTEM

Technical Field

The present invention relates to a digital
communications system which transmits a single-sideband
signal comprising modulated quadrature-related carriers.

Background of the Invention

Digital communication systems utilize a myriad of
modulation formats. In one commonly-used format, elements
of a data signal modulate quadrature-related carrier
signals. This type of modulation has a variety of names,
such as phase shift keying (PSK), quadrature amplitude
modulation (QAM), and asynchronous phase shift keying
(APSK). The information conveyed by the data signal is, of
course, virtually limitless and can include voice, video,
facsimile and the like. Moreover, the transmission channel
carrying the modulated carriers is also not limited and, at
present, may include air, wire or lightguide.

A problem in practically all communications
systems is that the transmission channel is band-limited.
That is, there is a finite frequency interval which can be
used to convey information. This limitation arises because
of system and/or device requirements. While the severity
of this problem does vary from system to system, it still
can be said that the ability to convey still more
information in a given frequency interval would be highly
desirable.

One technique to increase the information-
carrying capacity of a digital system transmitting
modulated quadrature-related carriers is to increase the
number of permissible modulation states. An example of
this technique is exemplified by the design and deployment
of 64 QAM systems in lieu of 16 QAM systems in applications
requiring greater capacity. The problem with this
technique is that the change in the number of modulation
states requires at least the design and development of new
modulators and demodulators. This effort is often

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expensive and the resulting equipment, at times, can not be
retrofitted into operational systems without great expense.

Another technique to increase system capacity has
been to utilize single-sideband signals instead of double-
5   sideband signals. This technique is rather simple to
implement and has been routinely used in formats which
modulate a single carrier signal. Unfortunately, this
technique has not been used for systems utilizing
quadrature-related carriers because there was no known way
10 of intelligently decoding the received signal after single-
sidebanding.

Summary of the Invention

The present invention is intended for use in
digital communications systems wherein elements of a data
15 signal modulate quadrature-related carrier signals. To
reduce the required bandwidth, the resulting modulated
quadrature-related carriers are transformed into a single-
sideband signal. After propagation through the
transmission channel, the received single-sideband signal
20 is demodulated into received signal elements. Each of
these elements includes an element of the data signal along
with a spurious signal introduced by the single-sideband
transformation. To recover the data signal elements, each
received signal element is altered to form at least one
25 estimate of the corresponding data signal element. Each
estimate formed is then compared against a set of
permissible data signal element values and the estimate is
outputted if a preselected criterion is met.

A feature of the present invention is that it can
30 be implemented within existing digital communications
systems to provide a substantial increase in information-
carrying capacity within some preselected bandwidth.

A further feature of the present invention is
that it can be used with conventional demodulation and
35 equalization techniques.

Brief Description of the Drawing

FIG. 1 is a block schematic diagram of a

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communications system which incorporates the present

invention;

FIG. 2 is a plot of the signal space diagram of

the signal levels transmitted by the communications system

5 of FIG. 1; and

FIG. 3 is a detailed schematic diagram of

decoders 118 or 119 shown in the communications system of

FIG. 1.

Detailed Description

10   FIG. 1 shows an exemplary QAM communications

system which incorporates the present invention. At

transmitter 10, a digital data signal on lead 120 is

coupled to QAM modulator 101. Within modulator 101,

serial-to-parallel converter 121 spreads successive data

15 signals on lead 120 over four paths 131,132,133, and 134.

Digital-to-analog (D/A) converter 122 quantizes the signals

appearing on leads 131 and 132 into a number of signal

voltages which appear on lead 135. Similarly, D/A

converter 132 quantizes the signals on leads 133 and 134

20 into a number of signal voltages which are coupled to

lead 136. Multipliers 127 and 128 receive the signal

voltages on leads 135 and 136 after they are respectively

smoothed by Nyquist filters 124 and 125. Multiplier 127

modulates the amplitude of a carrier signal generated by

25 oscillator 126 with the signals on lead 135 after

filtering. In similar fashion, multiplier 128 modulates

the amplitude of a second carrier signal with the signals

on lead 136 after smoothing by Nyquist filter 125. The

second carrier signal supplied to multiplier 128 is

30 generated by shifting the carrier signal generated by

oscillator 126 by minus $\pi/2$ radians via phase shifter 129.

Hence, the pair of carrier signals supplied to

multipliers 127 and 128 are in spatial quadrature to one

another and the products provided by multipliers 128 and

35 129 are each double-sideband signals. Summer 130 then adds

the products provided by multipliers 128 and 129 and

outputs this sum, also a double-sideband signal onto

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lead 102.

Reviewing the signal processing provided by the
transmitter components discussed thus far, it can be said
that these components modulate quadrature-related carriers
5 with elements of a data signal, wherein one element of the
data signal comprises the signals appearing on leads
131,132 or 135 or 137 while the other data signal element
comprises the signals appearing on leads 133,134 or 136 or
138. In addition, if we select the number and permitted
10 values of the signal voltages provided by D/A converters
122 and 123, we can graphically depict all of the possible
combinations of transmitted carrier signal amplitudes
which represent the data signal on a cartesian coordinate
plot. Such a plot is commonly referred to as a signal
15 space diagram.

Refer now to FIG. 2 which shows the signal space
diagram for the illustrative transmitter of FIG. 1. The
data signal element appearing on lead 137 is designated as
the "I" or in-phase element of the data signal while the
20 data signal element appearing on lead 138 is referred to as
the "Q" or quadrature element. As shown, the permissible
values of the "I" and "Q" elements are ± 1 and ± 3 volts and
all possible combinations of these permissible values form
16 signal states, designated as 201, in FIG. 2.

25   In prior art communications systems, the output
of summer 130 is coupled to a transmission channel which
propagates the information to system receiver 11. In
accordance with the present invention, a filter 103 is
added to the transmitter to convert the double-sideband
30 signal at the output of summer 130 into a single-sideband
signal thereby reducing the bandwidth required for signal
transmission. This bandwidth reduction also permits the
transmission of a second single-sideband QAM signal in the
recovered frequency interval. The resulting capacity of
35 two 16 QAM single-sideband signals is equivalent to that of
a 256 QAM double-sideband signal. The double-sideband to
single-sideband signal conversion, however, corrupts the

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operation of conventional QAM receiver circuitry and
additional functional capability is required in the
receiver to intelligently recover the data signal elements.
At this juncture, it should be understood that the present
5   invention is also applicable to radio systems wherein
additional circuitry is often disposed between summer 130
and the transmission channel to shift the frequency of the
transmitted carriers to a higher frequency band. Moreover,
the present invention is not limited to QAM systems and,
10   indeed, may be utilized in any system which transmits a
signal comprising modulated quadrature-related carriers
which are modulated in phase or amplitude or some
combination of phase and amplitude.

.To understand the principles of the present
15   invention, it is first necessary to consider the effects of
filtering one of the sidebands of the illustrative double-
sideband QAM signal and then transmitting the resulting
single-sideband signal through a transmission channel.

The QAM signal appearing at the output of
20   summer 130 can be expressed as a function of time $s(t)$
with

$$s(t) = i(t) \cos w_c t - q(t) \sin w_c t ; \qquad (1)$$

and where w_c denotes the frequency of the carrier
25   generated by oscillator 126, and

$i(t)$ and $q(t)$ respectively denote the values
of the I and Q data signal elements as a
function of time.

When $s(t)$ is passed through filter 103 with an impulse
30   response $h(t)$ in order to reject either one of the
sidebands, we can express the resulting single-sideband
signal as $[s(t)]_{SSB}$ with

$$35 \qquad [s(t)]_{SSB} = \int_{-\infty}^{+\infty} h(\tau) i(t-\tau) \cos[w_c(t-\tau)] d\tau$$

$$- \int_{-\infty}^{+\infty} h(\tau) q(t-\tau) \sin[w_c(t-\tau)] d\tau \qquad (2)$$

and where τ represents a dummy variable of integration.

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Using the trigonometric identities:

$$\cos[w_c(t-\tau)] = \cos w_c t \cos w_c \tau + \sin w_c t \sin w_c \tau \text{ and}$$
$$\sin[w_c(t-\tau)] = \sin w_c t \cos w_c \tau - \cos w_c t \sin w_c \tau, \quad (3)$$

5   equation (2) can be rewritten as:

$$
\begin{aligned}
[s(t)]_{SSB} = &\int_{-\alpha}^{+\alpha}\{h(\tau)i(t-\tau)\cos w_c \tau \, d\tau\}\cos w_c t \\
&+ \int_{-\alpha}^{+\alpha}\{h(\tau)q(t-\tau)\sin w_c \tau \, d\tau\}\cos w_c t \\
&+ \int_{-\alpha}^{+\alpha}\{h(\tau)i(t-\tau)\sin w_c \tau \, d\tau\}\sin w_c t \\
&- \int_{-\alpha}^{+\alpha}\{h(\tau)q(t-\tau)\cos w_c \tau \, d\tau\}\sin w_c t \quad (4)
\end{aligned}
$$

15   Equation (4), in turn, can be written as:

$$
[s(t)]_{SSB} = \frac{1}{2}\{i(t) + \hat{q}(t)\}\cos w_c t \\
\quad\quad - \frac{1}{2}\{q(t) - \hat{i}(t)\}\sin w_c t, \quad (5)
$$

where $\hat{i}(t)$ and $\hat{q}(t)$ are the Hilbert transforms of $i(t)$ and $q(t)$, respectively.

20   A comparison of equation (5) with equation (1) reveals that the effect of eliminating one of the sidebands of the QAM signal of equation (1) contaminates $i(t)$ with the Hilbert transform of $q(t)$ and contaminates $q(t)$ with the Hilbert transform of $i(t)$. Consequently, the

25   receiver of FIG. 1 must be provided with the capability of eliminating $\hat{q}(t)$ and $\hat{i}(t)$ to respectively recover the $i(t)$ and $q(t)$ components.

        Refer back to FIG. 1 and consider the general case where transmission channel 105 is dispersive and

30   introduces distortion comprising intersymbol interference (ISI), cross-rail interference (X-rail ISI) and Gaussian noise ($n(t)$). If $s(t)_{SSB}$ is coupled through a conventional QAM demodulator 107, two received data elements $i'(t)$ and $q'(t)$ are formed on leads 110 and 111.

35   The generation of $i'(t)$ and $q'(t)$ is accomplished by extracting the quadrature-related carriers from the received signal using well-known carrier recovery

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techniques. The signals on leads 110 and 111 can be
expressed as:
$$i'(t) = [i(t) + \hat{q}(t)] + ISI + X\text{-rail } ISI + n_I(t) \quad , \quad (6)$$
and
5    $$q'(t) = [q(t) - \hat{i}(t)] + ISI + X\text{-rail } ISI + n_Q(t) \quad , \quad (7)$$

with $n_I(t)$ and $n_Q(t)$ respectively representing the
Gaussian noise introduced into $i(t)$ and $q(t)$.
          The ISI and X-rail ISI in equations (6) and (7)
10 can be eliminated by coupling $i'(t)$ and $q'(t)$ through
conventional transversal equalizers 112 and 113 which are
configured to operate on $i'(t)$ and $q'(t)$ as if
$[i(t) + \hat{q}(t)]$ and $[q(t) - \hat{i}(t)]$ were the information
signals. The equalized signals $i_E(t)$ and $q_E(t)$
15 appearing at the output of equalizers 112 and 113 are then
sampled at the baud rate, 1/T, by sampler 114. The
k^{th} sample, where K is any integer, can be expressed
as
$$i_E(kT) = [i(kT) + \hat{q}(kT)] + n_{IE}(kT) \qquad (8)$$
20 for lead 116 and
$$q_E(kT) = q(kT) - \hat{i}(kT) + n_{QE}(kT) \qquad (9)$$
for lead 117. The expressions $n_{IE}(kT)$ and $n_{QE}(kT)$
represent the Gaussian noise in the received signal
components after equalization. Sampler 114 is controlled
25 by a timing signal on lead 108 which is supplied by
conventional timing recovery circuitry (not shown) in the
receiver.
          To recover the information carrying components of
$i(kT)$ and $q(kT)$, $\hat{q}(kT)$ and $\hat{i}(kT)$ must be eliminated. It
30 can be shown that $\hat{q}(kT)$ and $\hat{i}(kT)$ can only assume a limited
number of values and the values are a function of the
quantized values provided by D/A converters 122 and 123.
The set of values for $\hat{i}(kT)$ and $\hat{q}(kT)$ for any
communications system utilizing Nyquist filtering can be
35 expressed as
$$\hat{i}(kT) = -1/2q((k-1)T) + 1/2q((k+1)T) \qquad (10)$$
and

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$$\hat{q}(kT) = -1/2i((k-1)T) + 1/2i((k+1)T). \tag{11}$$

That is, the Hilbert transform of i(t) at the kth

5   sampling time is a function of q(t) at the (k-1) and (k+1)
sampling times wherein the (k-1) and (k+1) sampling times
are respectively one sampling time immediately preceding
and one sampling time immediately succeeding the kth
sampling time. And, the Hilbert transform of q(t) at the

10 k^{th} sampling time is a function of i(t) at the (k-1)
and (k+1) sampling times wherein the (k-1) and (k+1)
sampling times are respectively one sampling time
immediately preceding and one sampling time immediately
succeeding the kth sampling time.

15   From equations (10) and (11), it follows that in
the illustrative 16 QAM communication system wherein i(t)
and q(t) can take on the values of ± 1 and ± 3 volts, $\hat{i}(kT)$
and $\hat{q}(kT)$ can take on any value from the set {0, -1, -2,
-3, 1, 2, 3}. Therefore, at any sampling instant, kT,

20 $\hat{i}(kT)$ and $\hat{q}(kT)$ can assume one of seven possible values.
        Refer now to FIG. 3 which shows a detailed
schematic of the circuitry within decoders 118 and 119 of
FIG. 1. In decoder 118, the kth sample $i_E(kT)$ is
supplied to seven summers 301, 302, ... 307 to form seven

25 estimates of i(kT) on leads 311 through 317. Each summer
forms one of these estimates by subtracting a different one
of the seven possible values of $\hat{q}(t)$ from $i_E(kT)$. Each
of leads 321-327 supplies a different value of $\hat{q}(t)$ from a
source of reference voltages (not shown). Selection

30 circuit 318, comprising multiple threshold detectors,
compares each estimate against the permissible values of
.i(t), namely, ± 1 and ± 3 volts, and selects the estimate
of i(kT) which is closest to any of the permissible values.
This selected estimate is outputted on lead 150.

35 Decoder 119 performs an identical operation on each
sample $q_E(kT)$, with the estimate of q(kT) closest to one
of the permissible values of q(t) being outputted on

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lead 151 in FIG. 1. As shown, leads 150 and 151 couples the selected estimates of $i(t)$ and $q(t)$ to timing recovery and other receiver circuitry for further signal processing not connected with the present invention.

5   In the process of estimate formation and selection, it is possible for ambiguities to arise, i.e., there are two or more estimates formed which are equally close to different permissible data element values. This problem can be avoided by using one set of values for $i(t)$
10   and a different set of values for $q(t)$. For example, for the illustrative 16 QAM signal constellation shown in FIG. 2, values of $i(t)$ equal to ± 1 and ± 3 volts and the values of $q(t)$ equal to ± 1.5 and ± 4.5 volts provide signal states 201' which circumvent the aforesaid ambiguity
15   problem.

        While the disclosed decoders 118 and 119 comprise circuitry which simultaneously provides seven possible estimates of $i(t)$ and $q(t)$ using parallel signal processing, the decoders could comprise only one adder
20   which sequentially forms seven estimates of $i(t)$ or $q(t)$. In this approach, selection circuit 318 compares each estimate against the permissible values of a data element and any estimate which falls within a predetermined interval surrounding each permissible value would be
25   outputted. Upon selecting an estimate, selector circuit 318 would inhibit the outputting of any other estimate until the next sample is received from sampler 114.

        It should, of course, be understood that the
30   present invention is not limited to the particular embodiment disclosed and that numerous modifications will occur to those skilled in the art which are within the spirit and scope of the invention. First, for example, the use of transversal equalizers in the receiver is not
35   required if the magnitude of ISI and X-rail ISI is not large relative to the difference between permissible data element values. This is often true in lightwave and wire

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systems wherein the transfer function of the transmission
channel is not time-varying. Second, while Nyquist filters
are only shown in transmitter 10, half-Nyquist filters
could also be utilized in transmitter 10 and receiver 11.

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Claims

     1. Receiver apparatus for use in a digital transmission system wherein elements of a data signal modulate quadrature-related carriers and wherein said carriers are transformed into a single-sideband signal, said receiver apparatus comprising

     means for demodulating said single-sideband signal to form received signal elements by extracting said quadrature-related carriers, said received signal elements being different from said data signal elements due to the transformation of said carriers into a single-sideband signal; and

     means for recovering said data signal elements by forming at least one estimate of each of said data signal elements by altering one of said received signal elements by at least one preselected quantity and then comparing said formed estimate against a preselected criterion.

     2. The apparatus of claim 1 wherein said estimate formed for each of said data signal elements involves altering a different one of said received signal elements.

     3. The apparatus of claim 2 wherein said recovery means forms said estimate at selected times.

     4. The apparatus of claim 1 wherein each of said data signal elements have specific assigned values.

     5. The apparatus of claim 4 where said assigned values for all data signal elements are the same.

     6. The apparatus of claim 4 wherein said assigned values for one data signal element are different from said assigned values for any other data signal elements.

     7. The apparatus of claim 4 wherein said preselected quantity is a function of the assigned values.

     8. The apparatus of claim 7 wherein said function forms a set of numbers which comprises said preselected quantity.

     9. The apparatus of claim 1 wherein each

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received signal element includes one data signal element
and a nonzero function of another data signal element.

10. The apparatus of claim 9 wherein said nonzero
function is the Hilbert transform.

.5   11. The apparatus of claim 4 wherein said
preselected quantity lies in a set of numbers found by
taking an algebraic combination of all possible
permutations of said assigned values of one of said data
signal elements.

10   12. Receiver apparatus for use in a digital
transmission system wherein elements of a data signal
modulate quadrature-related carriers and wherein said
carriers are then transformed into a single-sideband
signal, said receiver apparatus comprising

15   means for demodulating said single-sideband
signal by extracting said quadrature-related carriers to
form elements of a received signal, each received signal
element including a selected element of said data signal
and a nonzero function of an unselected data signal

20 element; and
            means for recovering said data signal elements by
altering each received signal element by a plurality of
preselected amounts so as to form a set of values for each
received signal element and then picking one value from

25 each set in accordance with a preselected criterion.
            13. The apparatus of claim 12 wherein said
nonzero function is the Hilbert transform of the unselected
data signal element.

            14. A method of retrieving elements of a data

30 signal wherein said elements modulate quadrature-related
carriers and wherein said carriers are transformed into a
single-sideband signal, said method comprising the steps
of
            demodulating said single-sideband signal to form

35 received signal elements by extracting said quadrature-
related carriers, said received signal elements being
different from said data signal elements due to the

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transformation of said carriers into a single-sideband signal; and

recovering said data signal elements by forming at least one estimate of each of said data signal elements
5   by altering one of said received signal elements by at least one preselected quantity and then comparing said formed estimate against a preselected criterion.

15. A transmitter for use in communication systems comprising
10   means for modulating quadrature-related carrier signals with elements of a data signal to form a double-sideband signal, and

means for transforming said double-sideband signal into a single-sideband signal.

15   16. A communications system comprising a transmitter and a receiver wherein said transmitter comprises

means for modulating quadrature-related carrier signals with elements of a data signal to form a double-
20   sideband signal, and

means for transforming said double-sideband signal into a single-sideband signal, and

said receiver comprising

means for demodulating said single-sideband
25   signal to form received signal elements by extracting said quadrature-related carriers, said received signal elements being different from said data signal elements due to the transformation of said carriers into a single-sideband signal; and
30   means for recovering said data signal elements by forming at least one estimate of each of said data signal elements by altering one of said received signal elements by at least one preselected quantity and then comparing said formed estimate against a preselected criterion.

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FIG. 1

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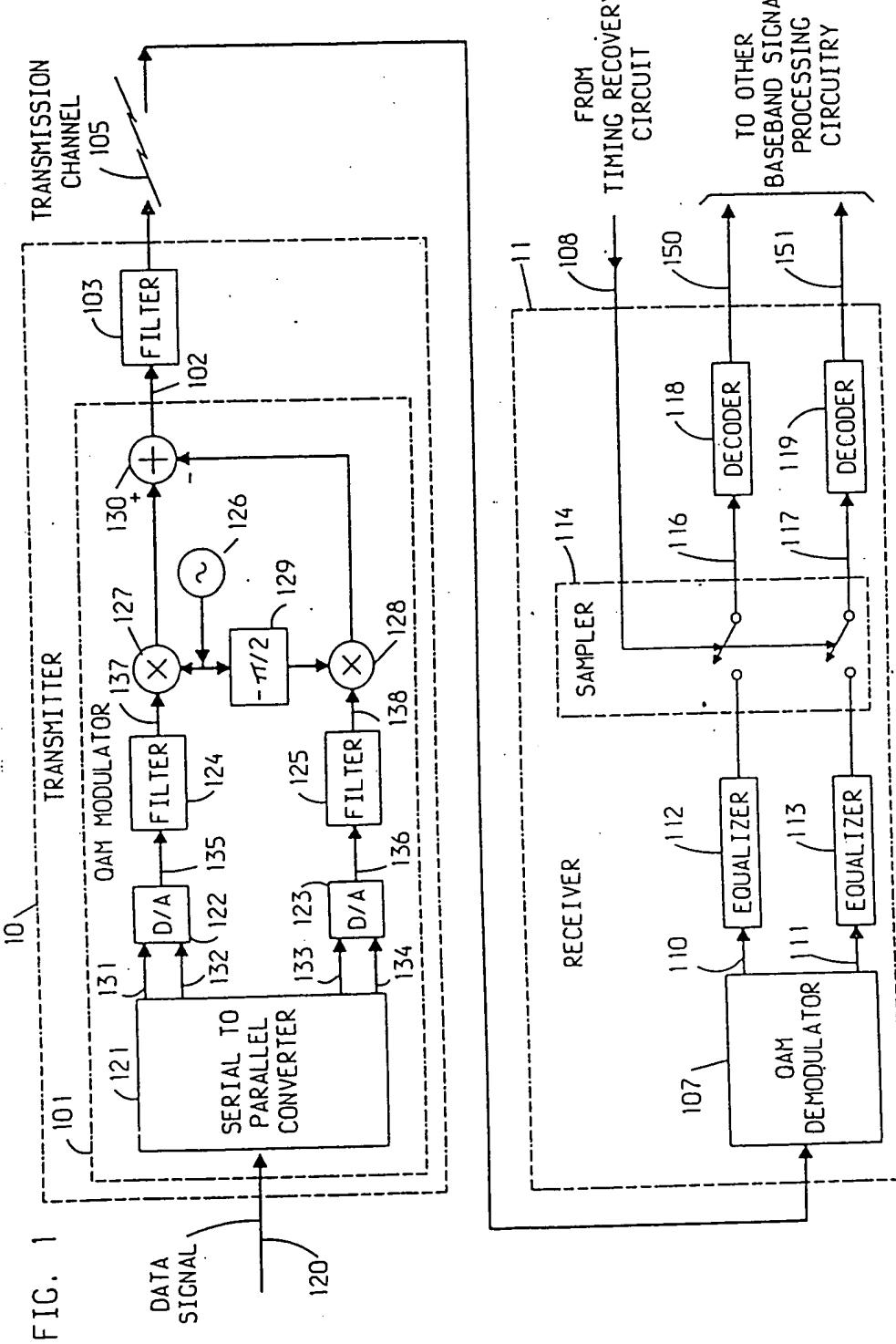
FIG. 2
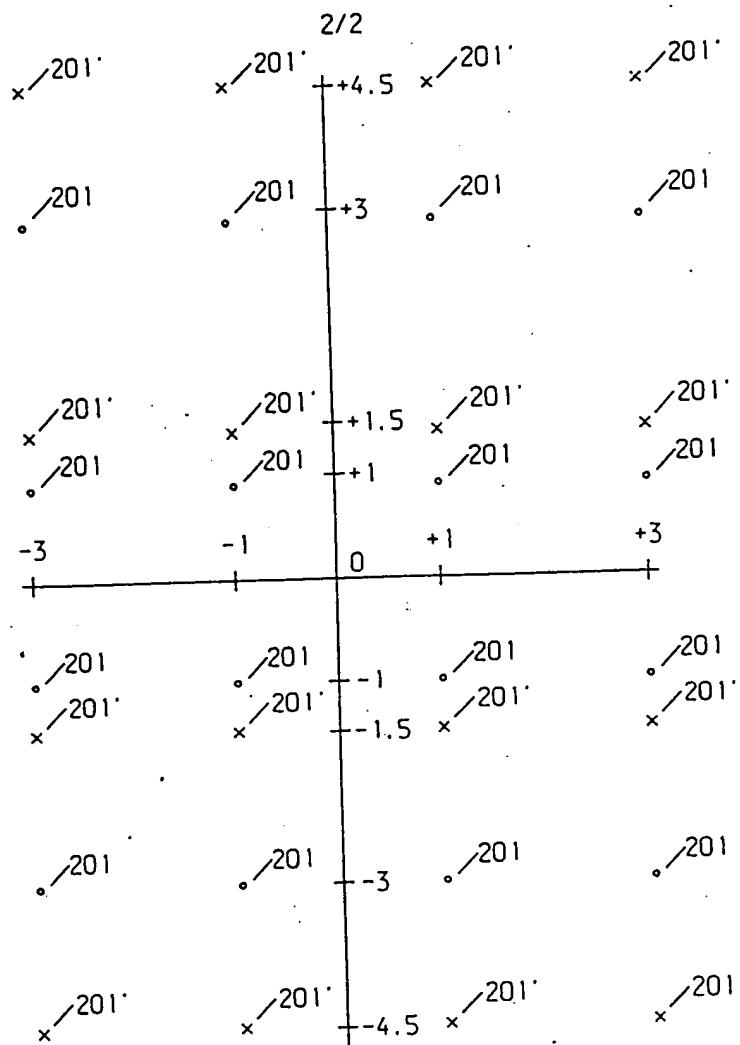
FIG. 3
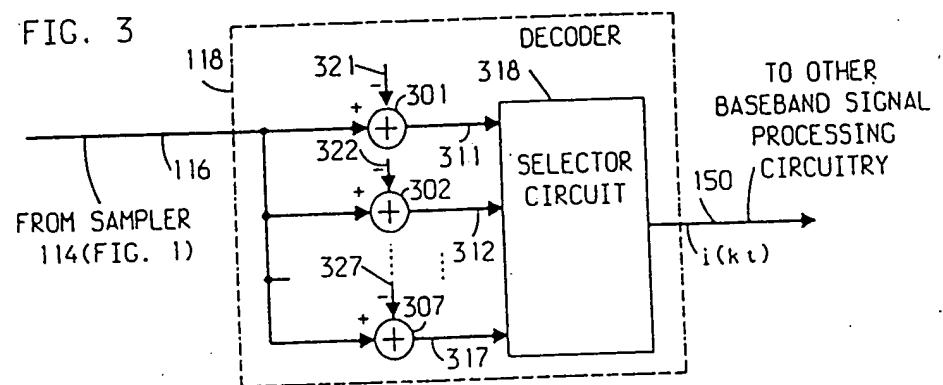
INTERNATIONAL SEARCH REPORT

International Application No PCT/US85/00302

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]
According to International Patent Classification (IPC) or to both National Classification and IPC
Int. CL.[3] HO4L 25/03 27/02 U.S. CL. 375/39, 43, 77

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	375/39,43,77,80,81 370/20 329/112

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category [*]	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
Y,P	US, A, 4,470,145 04 September 1984 Williams	1-16
X,P	US, A, 4,461,011 17 July 1984 Lender et. al.	15
Y	US, A, 4,439,863 27 March 1984 Bellamy	1-14, 16
X	US, A, 3,605,017 14 September 1971 Chertok et. al.	15
Y	US, A, 3,522,537 04 August 1970 Boughtwood	1-16
X	US, A, 3,443,229 06 May 1969 Decker	15
A	US, A, 3,849,730 19 November 1974 Ho	1-16

* Special categories of cited documents: [15]
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
12 March 1985	27 MAR 1985
International Searching Authority [1]	Signature of Authorized Officer [10]
ISA/US	Stephen Chin

Form PCT/ISA/210 (second sheet) (October 1981)